

On the field dependent surface resistance of niobium on copper cavities

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The surface resistance R_S of superconducting cavities prepared by sputter coating a thin niobium film on a copper substrate increases significantly stronger with the applied RF field compared to cavities of bulk material. A possible cause is that due to the thermal boundary resistance between the copper substrate and the niobium film R_S is enhanced due to global heating of the inner cavity wall. Introducing helium gas in the cavity and measuring its pressure as a function of applied field allowed to conclude that the inner surface of the cavity is heated up by only 60 ± 60 mK when R_S increases with E_{acc} by $100 \text{ n}\Omega$. This is more than one order of magnitude less than what one would expect from global heating. Additionally the effect of cooldown speed and low temperature baking have been investigated in the framework of these experiments. It is shown that for current state of the art niobium on copper cavities there is only a detrimental effect of low temperature baking. A fast cooldown results in a lowered R_S .

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I. INTRODUCTION

Superconducting cavities prepared by coating a micrometer thin niobium film on a copper substrate are currently used at CERN in the LHC and for the HIE-Isolde project¹. The operation temperature here is 4.5 K, where this technology enables a lower surface resistance than cavities prepared from bulk material. Other advantages of Nb/Cu cavities are lower material cost, no need for shielding the earth's magnetic field and enhanced thermal stability avoiding quenches². For quarter-wave resonators cryostat design is facilitated since these copper structures can be cooled by conduction¹.

Despite these advantages the Nb/Cu technology is currently not considered for accelerators requiring highest accelerating gradient E_{acc} like the ILC or lowest surface resistance R_S at temperatures of 2 K and below, especially for high duty cycle and CW applications. The reason is that R_S increases strongly with E_{acc} . The origin of this field dependent surface resistance has been subject of many studies in the past^{3–5}, but is still far from being fully understood. No single dominant source can be expected, thus several hypotheses need to be specifically addressed individually to identify their origin and possibly reduce their extent. In this paper the effect of a potential temperature difference between the inner cavity surface and the helium bath, induced by RF heating, is investigated. The influence on the RF performance of the cooldown speed and low temperature baking are addressed.

An issue in superconducting cavities is the possibility that the thermal impedance of the cavity wall leads to an increased temperature of the inner surface exposed to the RF, resulting in an increased surface resistance⁵. For bulk niobium cavities it has been shown that this effect at least contributes to the field dependent surface

resistance⁶. For Nb/Cu cavities the problem is even more complex, since the thermal impedance across the film/substrate interface is unknown and adds to the total thermal conductivity. Here a method previously tried in⁵ to directly measure the inner surface temperature of a superconducting cavity is studied in detail.

Thermal cycling has been studied in detail by several laboratories on bulk niobium^{7,8} and also on nitrogen doped niobium cavities⁸. It is however still unclear, what the ideal cooldown procedure is and if it depends on the material treatment of the cavity. Another open question is how much magnetic flux created by thermal currents influences R_S , which could be the reason for differences observed between vertical and horizontal test results⁷. Studies on Nb/Cu cavities are not only useful to push their performance, but also to obtain further information about the mechanism of thermal cycling in general, since Nb/Cu cavities are a lot less sensitive to ambient magnetic fields. At CERN such studies have been carried out using the Quadrupole Resonator^{9,10} on a Nb/Cu sample prepared by electron cyclotron resonance (ECR)¹¹ and HIE Isolde Nb/Cu quarter wave resonators¹². In this paper the first study on elliptical Nb/Cu cavities is presented. Results will be compared with the references given above and an advice for a cooldown procedure of cryomodules equipped with Nb/Cu cavities will be given.

Low temperature in-situ baking is used for bulk niobium cavities to shift the so called Q-drop (exponential increase of the surface resistance at high field) to larger values enabling economical high gradient operation¹³. In the medium field region above 10 MV/m Nb/Cu cavities also exhibit an exponential increase of R_S with E_{acc} . One might therefore argue that the origin for this is the same as for the Q-drop of bulk niobium cavities. To test this hypothesis the cavity used in this study was tested under same conditions before and after a 150 °C bake-out.

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II. EXPERIMENTAL SETUP AND PROCEDURE

A micrometer thin niobium film has been deposited by High-power Impulse Magnetron Sputtering (HIPIMS) technology on the inner surface of an elliptical single-cell TESLA type¹⁴ 1.3 GHz copper cavity produced by spinning and electropolishing. The important cavity parameters for the studies presented here are found in Tab. I. They relate the peak magnetic and electric fields to the accelerating gradient E_{acc} and the unloaded quality factor Q_0 to the surface resistance R_S . In the following always E_{acc} and R_S will be used. The HIPIMS approach is under investigation at CERN since 2010¹⁵. So far the results show systematically an increase of R_S with E_{acc} similar to what has been observed in the past for cavities coated by dc magnetron sputtering (dcms)³. For the vertical cold tests the cavity has been equipped with an input coupler with a $Q_{ext} = 2 \times 10^9$ and a pick-up antenna with $Q_{pick-up} = 3 \times 10^{11}$. The external coupling Q_{ext} was chosen to obtain critical coupling at 1.8 K and $E_{acc} \approx 15$ MV/m. RF measurements were performed using the phase locked loop technique¹⁶. Temperature sensors were mounted above and below the cavity cell to measure the temperature and its gradient during the phase transition from the normal to the superconducting state. The vertical bath cryostat has been equipped with a mu-metal shield to reduce the ambient magnetic field to about $3 \mu\text{T}$. Helium was transferred using standard dewars pressurized with helium gas. For the initial cooldown the gas overpressure was set to about 200 mbar. During this first helium transfer the dewar was emptied when the cavity temperature was about 50 K. This lead to a thermalization of the cavity. The temperature gradient at the phase transition was the lowest of all cooldowns performed, see Fig. 1.

In total the cavity was cooled down five times. Each cycle started with a measurement of R_S as a function of E_{acc} at 4.2 K. Then the cavity was further cooled down to 1.8 K by pumping the helium bath to 16.5 mbar. This process takes several hours, which is slow enough to take several measurements of R_S at $E_{acc}=1$ MV/m. After the initial cooldown the cavity was warmed up twice above T_c and cooled down again. During each warmup the quality factor was measured with a network analyzer to ensure that the whole cavity was in the normal conducting state before the helium transfer was restarted. The maximum temperature the cavity reached in these cycles never exceeded 20 K. For the first thermal cycle the overpressure was set relatively high to about 250 mbar on the helium supply dewar, while for the second cycle the overpressure was set to only 50 mbar to reduce the cooldown speed.

TABLE I. Parameters of TESLA type cavities¹⁴

Geometry Factor G	270 Ω
E_{peak}/E_{acc}	2.0
B_{peak}/E_{acc}	4.26 mT/(MV/m)

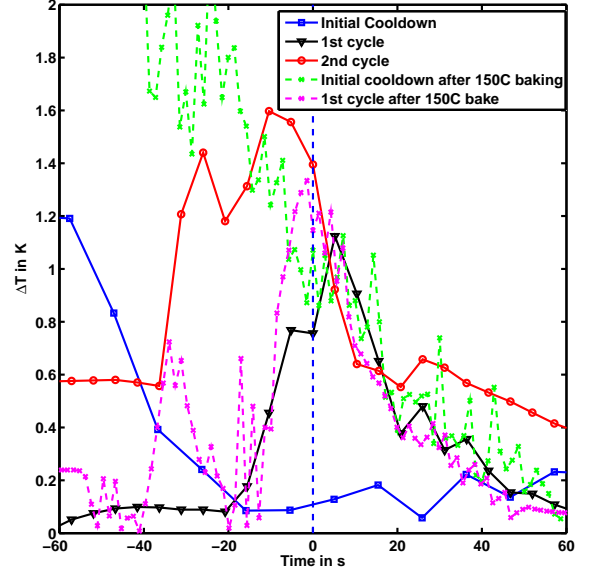


FIG. 1. Temperature gradient along the cell from one minute before until one minute after the phase transition for five cooldowns.

Figure 1 displays the temperature difference between the upper and the lower sensor from one minute before until one minute after the phase transition for the three cycles. The cooldown speed was about 70 mK/s for the initial cooldown and the second cycle and 230 mK/s for the first cycle.

After the initial cooldown several additional scans of R_S vs E_{acc} were performed just below and above the lambda point of helium at 2.17 K. During the warmup to room temperature the frequency shift was measured as a function of temperature to derive the penetration depth. For this the helium was almost completely evaporated so that the whole cavity was only cooled by helium gas. A few liters left on the bottom allowed to obtain a constant temperature along the cavity by evaporating some of the liquid. For a precise measurement pressure control is extremely crucial. A PID-controlled butterfly valve was used to pump the bath pressure to 80 mbar. A stability better than 0.02 mbar was achieved during the whole measurement. After complete warmup the cavity was in situ baked at 150°C for 50 h. In the following RF tests only one thermal cycle with a fast cooldown has been carried out. The speed was 110 mK/s for the initial cooldown and 330 mK/s for the thermal cycle, after which an additional measurement was performed. Helium gas was introduced in the cavity. At 1.8 K its pressure was $p_{RT}=5 \times 10^{-5}$ mbar measured at the top flange connection of the cryostat, which corresponds, according to the thermal transpiration law

$$p_{cav} = p_{RT} \sqrt{\frac{T_{cav}}{T_{RT}}} \quad (1)$$

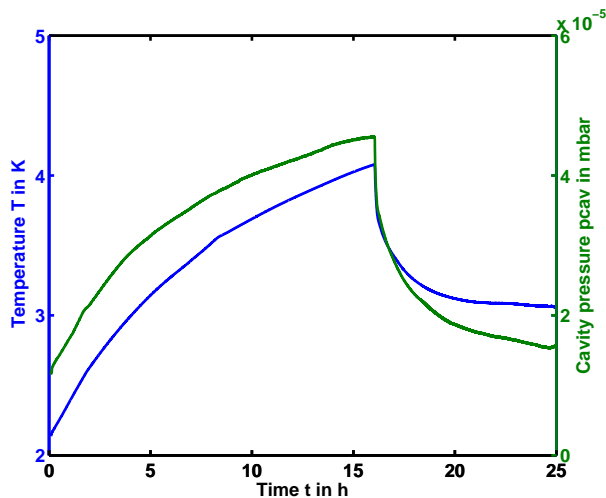


FIG. 2. Temperature and pressure in the cavity during warmup and following cooldown measured as a function of time.

to a cavity pressure $p_{\text{cav}} = 4 \times 10^{-6}$ mbar, where T_{cav} and T_{RT} are the cavity and the room temperature, respectively. The surface resistance was once again measured as a function of E_{acc} , now with the helium gas inside the cavity. To test whether the temperature of the cavity's inner surface increases with E_{acc} the helium pressure was recorded. In order to calibrate the pressure to temperature values during the following warm-up both quantities were recorded. A clear correlation was found, see Fig. 2. To verify that the pressure increase was not caused by a leak introducing just more helium gas with time the helium bath was pumped down again. Once more a clear correlation between p and T was found, see Fig. 2. For the cooldown lower pressures were measured for the same temperatures, which can be correlated to the lower helium level in the cryostat. The gas in the now warmer region of the pumping line is expanding more and contributes to the total pressure. For the calibration of p with respect to T only the values obtained during warm-up were used. These have been recorded at almost the same liquid helium level as the R_S and p vs. E_{ac} measurement directly before. The data and a linear fit are displayed in Fig. 3. The physical mechanism, which is responsible for the pressure increase as a function of temperature involves temperature dependent adsorption on the cavity wall and expansion of the non-adsorbed gas with temperature. The pressure of $p_{\text{cav}} = 4 \times 10^{-6}$ mbar was chosen to be high enough that the surface was saturated with helium and a temperature increase results mainly in an increase of the pressure of the non-absorbed gas. Based on data from¹⁷ it can be estimated that at the pressure used only a fraction of about 10% can be absorbed by the cold cavity surface. An even higher pressure has been tried but resulted in strong discharging at a few MV/m making the measurement impossible. Saturation of the cold surface is important when the pressure

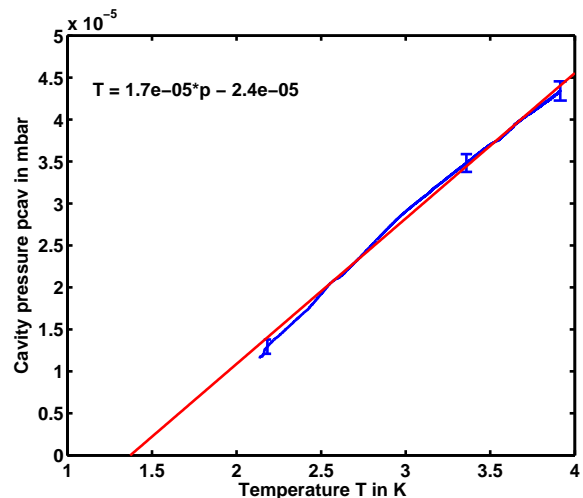


FIG. 3. Cavity pressure as a function of temperature measured during warm-up. The blue line represents measurements obtained every 10 s, while the red line shows a linear fit to the data.

increase of the global warming of the cavity due to warming of the helium bath for calibration is compared with the pressure increase due to heating from RF. For example if one would heat up by RF only the cavity cell releasing gas from its surface it could be adsorbed by the non-saturated cut-off tubes remaining at bath temperature. In this case a warming of the cavity cell could mainly result in an increase of the adsorbed gas on the cut-off tube surfaces. The linear dependence measured between p and T (Fig. 3) suggests that the ideal gas equation is indeed applicable and the surfaces are well saturated.

III. RESULTS

A. Low field surface resistance

For each cooldown cycle the surface resistance was measured as a function of temperature at $E_{\text{acc}} = 1$ MV/m, see Fig. 4. The data has been fitted to BCS theory using the WinSuperFit software based on calculations from Halbritter¹⁸. As input parameters the critical temperature $T_c = 9.41$ K, the London penetration depth for infinite mean free path $\lambda_L = 32$ nm and the BCS coherence length $\xi_0 = 39$ nm were used. The former quantity was obtained from frequency shift measurements (see below), while the latter two were taken from the literature¹⁹. Three parameters were varied in a least squares fit, see Tab. II. The smallest residual resistance R_{res} was obtained for the fastest cooldown. The effect is however relatively small. The low temperature bake-out yielded an increase of R_{res} by several n Ω . The mean free path could not be accurately determined from R_S vs. T , because it was not known whether the mean free path is larger or shorter

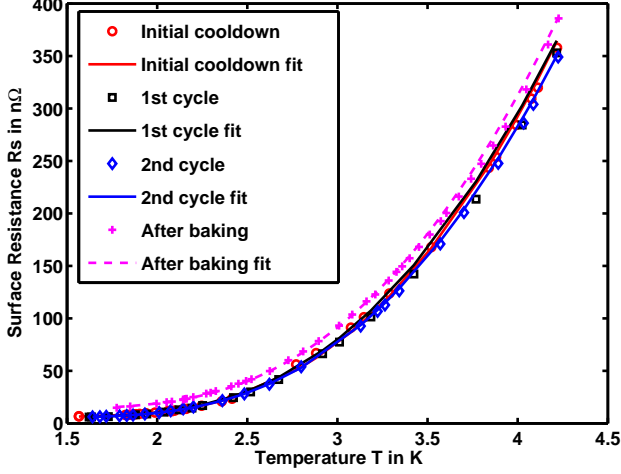


FIG. 4. Surface resistance R_S of a 1.3 GHz Nb/Cu cavity as a function of temperature measured after initial cooldown and two following thermal cycles above T_c .

than the coherence length. For thin film cavities this is not obvious, especially not after low temperature baking. From a measurement of the frequency shift, see Fig 5 however one can determine l independently even though it has to be noted that here the information depth is different (several 100 nm) than for the R_S vs. T measurement (about 50 nm). From a least squares fit to the Gorter-Casimir expression²⁰

$$\lambda(T) = \frac{\lambda_0}{\sqrt{1 - (T/T_c)^4}} \quad (2)$$

λ_0 and T_c are derived. From λ_0 the electron mean free path l can be obtained from an expression found by Pippard²¹:

$$\lambda(l) = \lambda(l \rightarrow \infty) \sqrt{1 + \frac{\pi \xi_0}{2l}}. \quad (3)$$

The London penetration depth $\lambda_L=32$ nm and the BCS coherence length $\xi_0=39$ nm were taken once more from literature¹⁹. This measurement shows that the low temperature baking significantly decreases l , see Tab. II. The BCS surface resistance is only slightly altered because it has its minimum at $l=\xi_0$ ¹⁹.

B. Field dependent surface resistance

Figure 6 shows R_S as a function of E_{acc} at 1.8 K for five cooldown cycles, including two after baking. At low field the surface resistance differs only by a few nΩ as one can also see from Fig. 4. At larger values of E_{acc} the differences in R_S become more pronounced. The lowest value is obtained for the fastest cooldown (1st cycle) before baking. Baking enhances R_S significantly, especially

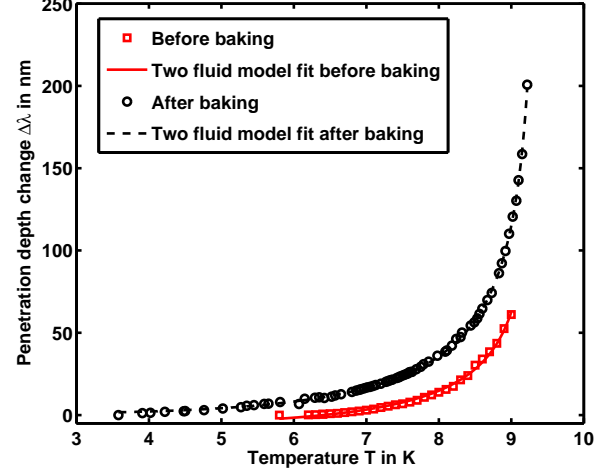


FIG. 5. Penetration depth change as a function of temperature measured before and after baking.

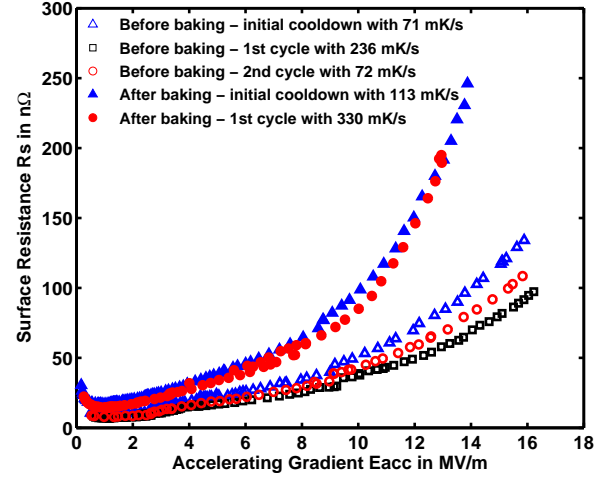


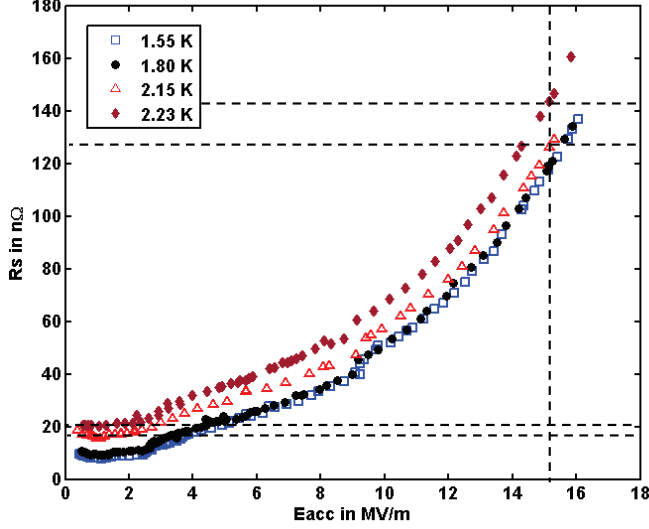
FIG. 6. Surface resistance R_S of a 1.3 GHz Nb/Cu cavity measured at 1.8 K before (open symbols) and after baking (closed symbols) for initial cooldown and several thermal cycles above T_c .

at higher field. After baking R_S is again reduced by fast cooldown, even though the effect is less pronounced as before.

After the initial cooldown R_S was additionally measured as a function of E_{acc} for several temperatures just above and below the lambda point of helium at 2.17 K, see Fig. 7. One can see that at low field R_S varies only slightly for the different temperatures. However for higher accelerating gradients R_S increases stronger with E_{acc} if the helium bath is not superfluid. Between 1.55 and 2.13 K the temperature dependent BCS surface resistance changes by a factor of about 15 from about 1 to approx 15 nΩ, see Fig. 4. The increase of R_S with E_{acc} on the other hand is very similar for the curves of 1.55,

TABLE II. Fit parameters obtained from low field surface resistance and penetration depth change measurement

	initial cooldown	1st cycle	2nd cycle	after baking
$\Delta/(k_b T_c)$	1.96 ± 0.03	1.90 ± 0.05	1.93 ± 0.01	1.89 ± 0.01
R_{Res} in $\text{n}\Omega$	6.1 ± 0.2	5.2 ± 0.2	5.5 ± 0.2	13.7 ± 0.4
l in nm from R vs T	85 ± 40	25 ± 120	25 ± 120	27 ± 130
λ_0 in nm			46 ± 4	78 ± 1
l in nm from $\Delta\lambda$			58 ± 4	12 ± 1
T_c	-	-	9.41 ± 0.05	9.41 ± 0.02

FIG. 7. Surface resistance R_S of a 1.3 GHz Nb/Cu cavity measured at four different temperatures. At low field R_S is similar for the four temperatures. At higher field R_S increases more strongly if data is taken at temperatures above the lambda point. Compare the horizontal dashed lines.

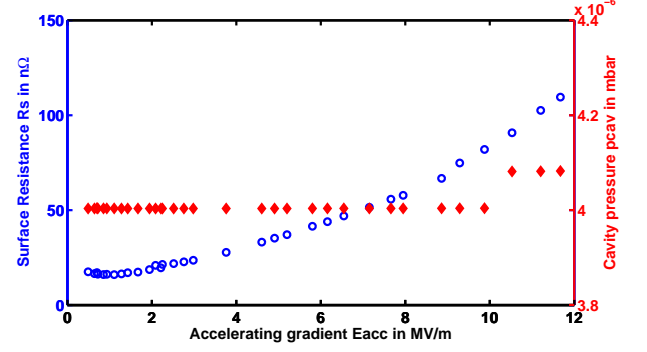
1.8 and 2.13 K, see Fig. 7. This shows that the field dependent surface resistance of Nb/Cu cavities is at least dominated by the residual resistance.

After baking and the following thermal cycle the cavity was filled with helium gas. Then R_S vs. E_{acc} was measured again and also the helium pressure was recorded, see Fig. 8. The resolution of the pressure sensor was only 2 digits which resulted with the calibration obtained during the following warm-up (Fig. 3) in a resolution of 60 mK. Above 10 MV/m a pressure increase by 0.1×10^{-6} mbar was detected, corresponding to a temperature increase of 60 ± 60 mK.

IV. DISCUSSION

A. Thermal Cycling

It was shown that fast cooling can reduce the surface resistance of elliptical Nb/Cu cavities by about 20 % at $E_{\text{acc}} = 15$ MV/m in a vertical test cryostat. Thermal cycling changes the low field residual resistance only slightly by fractions of a $\text{n}\Omega$. The benefit is only at higher ac-

FIG. 8. Primary y-axis: Surface resistance R_S of a 1.3 GHz Nb/Cu cavity measured at 1.8 K. Secondary y-axis: Helium pressure p inside the cavity as a function of E_{acc} .

celerating gradients, similar to what has been observed in⁸ for low temperature baked 9-cell bulk niobium cavities. However for the Nb/Cu cavity investigated here this effect was reduced by baking. Furthermore it has to be noted that the cooldown speed was at maximum 30 mK/s in⁸ which is not even half as fast as the lowest cooldown speed of 70 mK/s obtained in the experiments here. In⁷ it took at least one minute between the transition from the coldest to the warmest part of the cavity, here this was at maximum a few seconds. In¹¹ it was found by measurements using the CERN Quadrupole Resonator on a Nb/Cu sample prepared by electron cyclotron resonance (ECR) that a fast cooldown decreases R_S . The cooldown speed obtained in this experiment was comparable to what has been reported here. However it was found in contradiction to the results presented here that mainly the low field R_S is affected, while the influence on the field dependence is rather small. The results presented here suggest that the thermal gradient does not affect R_S but the cooldown speed is of importance, which is in contradiction to what has been measured on Nb/Cu quarter wave resonators in vertical tests¹². To conclude it can be said that the cooldown speed and the thermal gradient play an important role for minimizing losses in superconducting cavities. Comparing results from different publications is difficult because it is still unclear whether flux trapping from ambient fields or thermal currents are more relevant. Another open question is whether cavities of different geometry and/or different materials/treatments need specific cooldown procedures. Based on the results presented here and taking into account that thermal cur-

rents might be more relevant in horizontal cryomodules than in vertical test cryostats the following procedure for horizontal SRF cryomodules equipped with Nb/Cu cavities is advised:

- After the initial cooldown a warmup just above T_c ,
- Give the cavity time to thermalize to minimize thermal currents,
- Cooldown the cavity as fast as possible through T_c .

This procedure is consistent with all experimental results on Nb/Cu cavities. In⁷ it was suggested to either thermalize the cavity above T_c during the first cooldown or perform a thermal cycle. The former option is not advised for Nb/Cu cavities. The thermalized cavity in the first initial cooldown gave an even worse result than for the slowest cycle afterwards.

B. Low temperature baking

In situ baking of the cavity yielded a higher low field residual resistance and an enhanced field dependent surface resistance, while the temperature dependent BCS surface resistance R_{BCS} was almost unaffected. The former two effects have also been observed for bulk niobium cavities¹³. For bulk niobium cavities R_{BCS} is lowered by baking, which can be correlated to a decreased mean free path l . An unbaked bulk niobium cavity has $l \gg \xi_0$. Baking pushes l closer to ξ_0 . For Nb/Cu cavities baking also reduced l , but since these cavities already have $l \approx \xi_0$ before baking there is no reduction of R_{BCS} . For bulk niobium the low temperature bake is beneficial because it shifts the exponential increase of the surface resistance referred to as Q-Drop to higher fields. Since the baking did not have any similar effect for the Nb/Cu cavity it can be concluded that the origin of the field dependent surface resistance here is a different one than for the Q-drop of bulk niobium cavities. Currently there is no benefit from in situ baking of Nb/Cu cavities. It might however become useful if the medium field Q-slope could be understood and cured and the Q-drop as observed for bulk niobium cavities would become the limitation of this technology.

C. Thermal resistance

Measurements of R_S as a function of E_{acc} just below and above 2.17 K the lambda point of helium have shown that the thermal resistance plays a role for the losses in Nb/Cu cavities cooled by helium-I. At 15 MV/m the surface resistance is about 20 n Ω higher if the cavity is only cooled by helium-I. In helium-II however the contribution to the overall field dependent surface resistance seems to be rather low. An increase of the inner surface temperature of only 60 \pm 60 mK was measured. It has to

be noted that for the calibration of the gas pressure with respect to the temperature the whole cavity including a part of the pumping line was warmed up and for the RF measurement only the part of the cell with high surface magnetic field. The ratio of these surface areas is roughly two. Taking this into account the heating of the inner surface can at maximum account for an additional R_S of 6 n Ω assuming low field BCS losses. On the other hand an increase of 100 n Ω was measured between low field and 15 MV/m. It can be concluded that the thermal resistance can play an important role in minimizing the losses of superconducting cavities at high field. The thermal boundary resistance between the Nb film and the copper substrate is however not the main contribution for the field dependent losses of Nb/Cu cavities. In fact the thermal resistance should play a more important role for bulk niobium cavities. In⁵ it has been reported that the overall thermal conductance of a niobium film on a copper substrate is still four times higher than of electropolished niobium. Even for bulk niobium cavities operated in helium-I it had been concluded by thermal modeling that heating of the inner surface only plays an insignificant role²².

The method to measure the gas pressure as a function of the accelerating gradient allowed to derive the inner surface temperature and to calculate an upper estimate how much the heating of the inner surface accounts for the field dependent surface resistance. The experiments presented here were limited by the two digit resolution of the pressure sensor and therefore only allowed to conclude that global heating is not the main contributor to the field dependent surface resistance of Nb/Cu cavities. Further experiments with enhanced resolution and also on bulk niobium cavities are planned to study this effect in more detail. The method has already been tested on an LHC crab cavity and a significant pressure increase was detected. These results will be presented elsewhere. The method might also be used to obtain the quality factor Q_0 in horizontal cryomodule tests equipped with strongly coupled input antennas. In this case one could first measure Q_0 vs E_{acc} and p in a vertical test cryostat. After installation in the cryomodule one could insert gas in the cavity again and measure E_{acc} and p again and then obtain Q_0 by comparison with the results from the vertical test. This could serve as an independent method to the usual approach of obtaining Q_0 from the liquid helium consumption.

V. CONCLUSION

It has been shown that a fast cooldown can significantly reduce the surface resistance of Nb/Cu cavities. There is currently no benefit from low temperature baking for this technology. The thermal resistance plays only a minor role for the field dependent losses if the cavity is cooled by helium-II. It can be concluded that the field dependent surface resistance of Nb/Cu is mainly limited by

effects intrinsic in the film, which need to be investigated in detail if the current limitations shall be overcome.

VI. ACKNOWLEDGMENT

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